Fermilab
RD/MSD/Engineering Analysis Group
MS219, P.O.Box 500,Batavia, IL60510

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Failure Analysis for 1.8 m Vacuum Window (Ktev)

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1. Introduction

The 1.8 m diameter circular vacuum window used in the Ktev experiments was centrally penetrated with a steel arrow while under vacuum to investigate the ensuing failure mode. It was expected that mylar layer of the kevlar/mylar window would be broken by the arrow, and that the kevlar would gradually return to it's original position as the vacuum was slowly released. However, the window failed catastrophically, ripping the kevlar fabric completely across the window diameter. It was suspected that the arrow, due to it's size and the large distance (3 inches) that it was driven into the window, did not simply pierce the mylar but precipitated the rupture of kevlar fibers in it's immediate neighborhood and the subsequent violent failure. This report will describe the stress analysis supporting this view.

2.Vacuum Load

Since the window suddenly failed after a 3 inch displacement at it's center (in addition to the displacement already present due to vacuum) one way to look at this problem is to find out whether this extra displacement will cause a severe stress in the kevlar fibers. A finite element model was created as shown in Figure 1. The Poisson's ratio is modified to simulate individual fiber behavior, and the window is assumed to resist lateral loads only through membrane stress, with no bending. The vacuum load is applied first to obtain an initial state for the second load step in which the center of window is pushed down another three inches. It is found that the window stresses are well below failure stresses with a 15 psi load. The maximum stress occurs in the center of the window with a value of 180 ksi. The center deflection is about 5.5", which is comparable to the measurement of the test result.

In order to validate the modeling work in further, a sub-model technique was used to model the center of window in great detail as shown in Figure 2. The rectangular area is about 5"x 5" measured from the center. The kevlar fiber cloth is modeled by a mesh of cable elements, which can sustain tension only. Each cable element models of 2 yarns of the kevlar. (The 34 yarns/in becomes 17 cables/in). Away from this region the mesh converts to the membrane shell elements used in the first model. It was found that the maximum stress is about 173 ksi with a value of 5.45" maximum deflection. These numbers compare very well with the first model.

3. Vacuum Load with a 3" Extra Displacement

The membrane shell element model under vacuum load was given a displacement of three inches at it's center, tapering radially outward at a 45 degree angle to represent the actual arrow profile. It is no surprise to see that a very large stress occurs in the center of the window. At a radius of 1" from the center, the stress reaches 1 million psi. This is 2.5 times higher than the tensile strength published by DuPont for Kevlar 29. It is clearly shown that the window designed for 15 psi can not sustain such extra displacement, especially in the center.

During the stretching process, fiber located in or near the center of the window reaches its tensile strength first and breaks at its weakest point. The fiber next to it will pick up the extra load and become overloaded and break also. Thus, a so-called " chain reaction" takes place. All of this could happen in a very short time of the period, and explains how the cloth-type window fails. The question which must be answered is why the vacuum load on the window could remain for the time needed to rupture the window so severely when the window failure itself should be relieving that vacuum. One explanations is that the chain reaction is started within the kevlar fiber first due to the extra stretching, while mylar layer is still nearly entirely intact because of its ductility. Thus the vacuum load remains basically unchanged for the brief time needed for fiber failure to propagate outward to the window boundaries. The damaged area gets larger and larger until the mylar is no longer able to hold vacuum load and raptures instantaneously. A large amount of the air rushes into the chamber to initiate a possible shock wave so that the window bounces back scattering broken pieces everywhere.

Let us considering the reverse (and intended) case in the advance of the arrow is stopped when the mylar is breached. The vacuum load begins to discharge immediately and the kevlar fibers, which are not under the additional stress of the 3 inch displacement, will not break, although a few may be cut by the arrow. The release of vacuum is further slowed by the filter-like behavior of the kevlar fabric and nothing will happen except the window goes back to the original position.

4. Vacuum Load with a Hole in the Center of Window

As a further interesting study of the chain reaction scenario, a finite element model was created with a hole in the center of the window. By applying a vacuum load (15 psi), it was noticed that the stress around the hole increases as the hole size gets larger. Maximum stress reaches 300 ksi for the case of a half inch diameter hole. If one considers this as a breaking point, the fiber around the hold will break first and hole size becomes larger. Again, fiber stress around the new hole is even higher and fibers again break. The propagation of this fracture wave will not be stopped until the loading is discharged.

5. Summary

The cause of the window's explosive type of failure could be very complex. The study here only addresses it from the stress point of view. Many other factors may play a significant role. Therefore, a similar test with a much sharper arrow is strongly recommended in order to verify or understand the above argument. The sharp and narrow arrow is a crucial to the test as it will make the mylar break without stretching the kevlar. It is expected that the explosive failure will not occur, and that the window will slowly release vacuum and return to it's initial position.

All calculations are summarized in the Table-1. The plots of finite element result are attached in Appendix A.

Table-1 Summary of Calculation Results

Load	15 psi	15 psi + extra 3"	30 psi
max. stress (psi)	0.18E6	1.68E6	0.29E6
max. deflection (in)	5.5	8.5	7
SF (1) *	2.2	Fail	1.38
SF(2) *	1.7	Fail	1.05

* Note: SF (1) is calculated based on the tensile strength = 400,000 psi for the kevlar 29 ; SF (2) is calculated based on the tensile strength = 1800 lb/in from weave company.

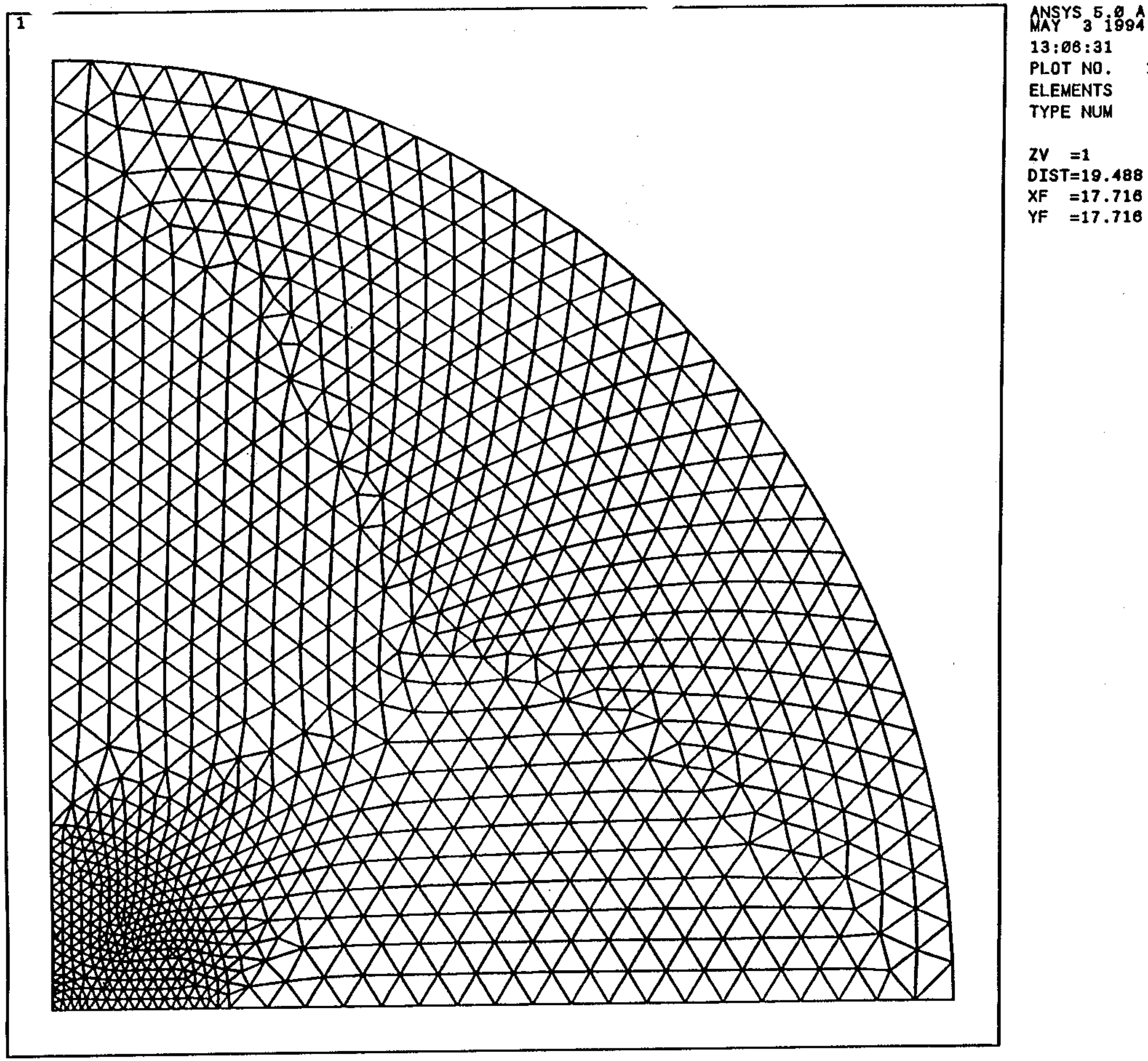


Figure 1 Finite Element Model for 1.8 m window (kevlar only)

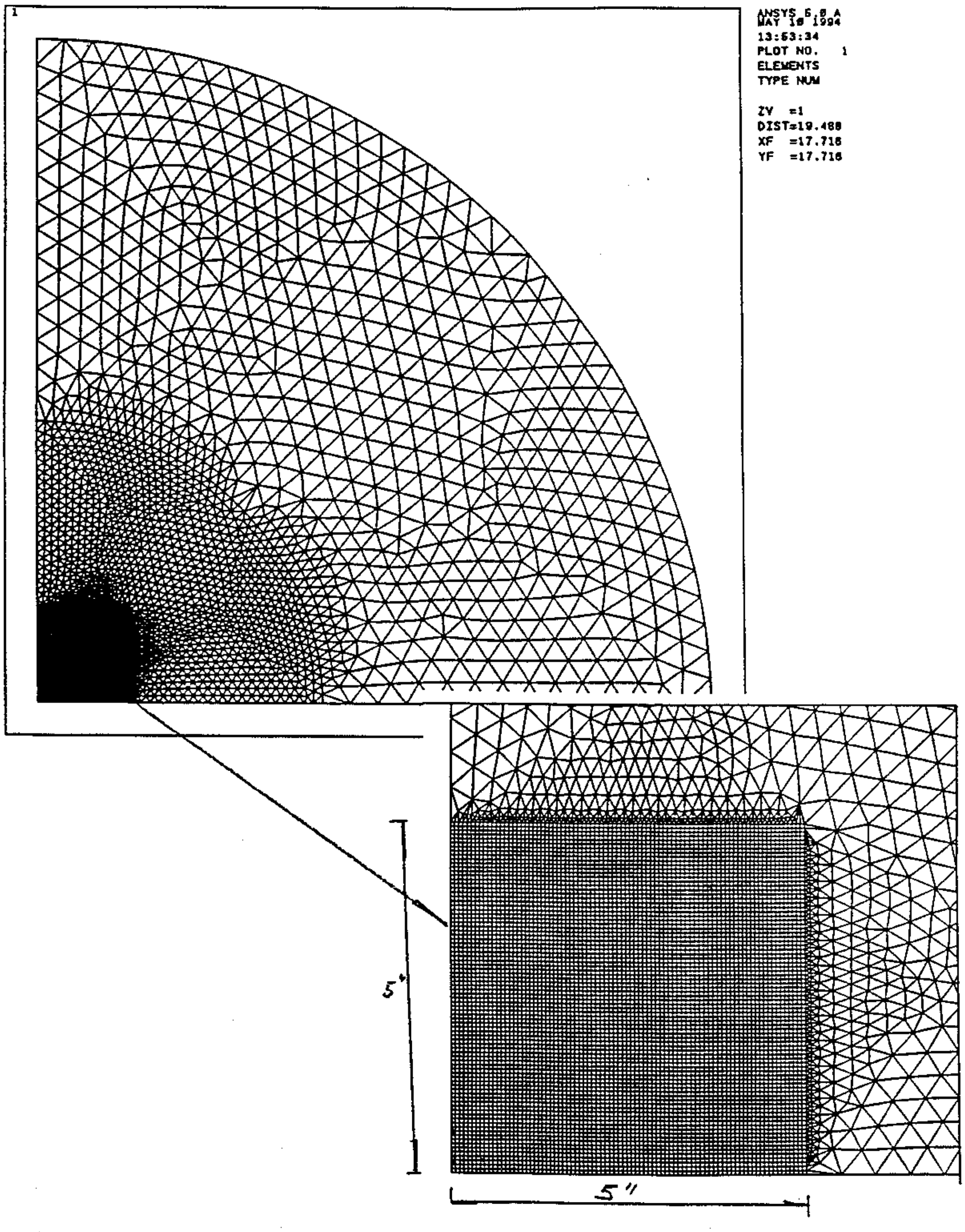


Figure 2. sub-model of 1.8 m window

Appendix A:

Plots from Finite Element Result

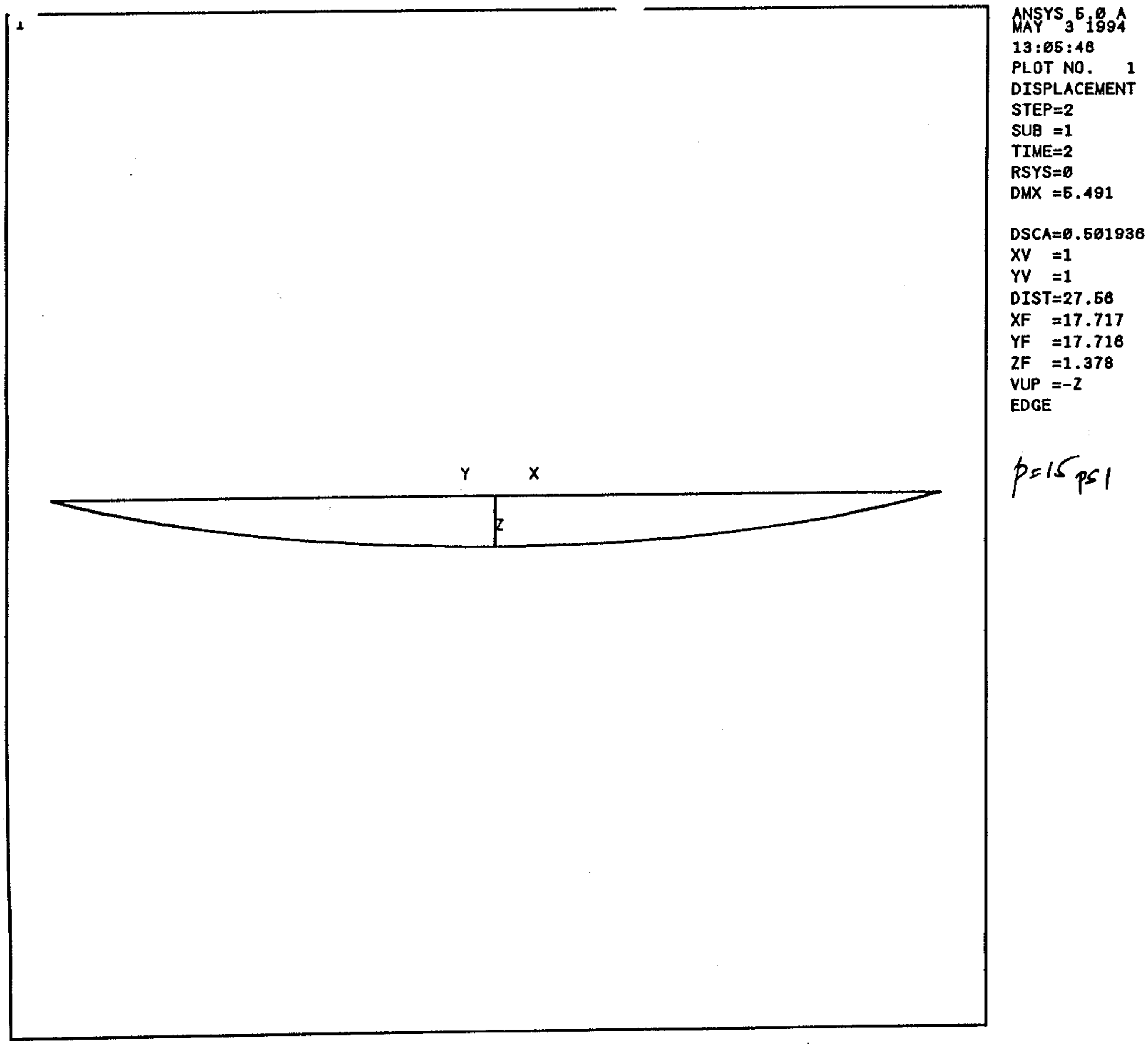
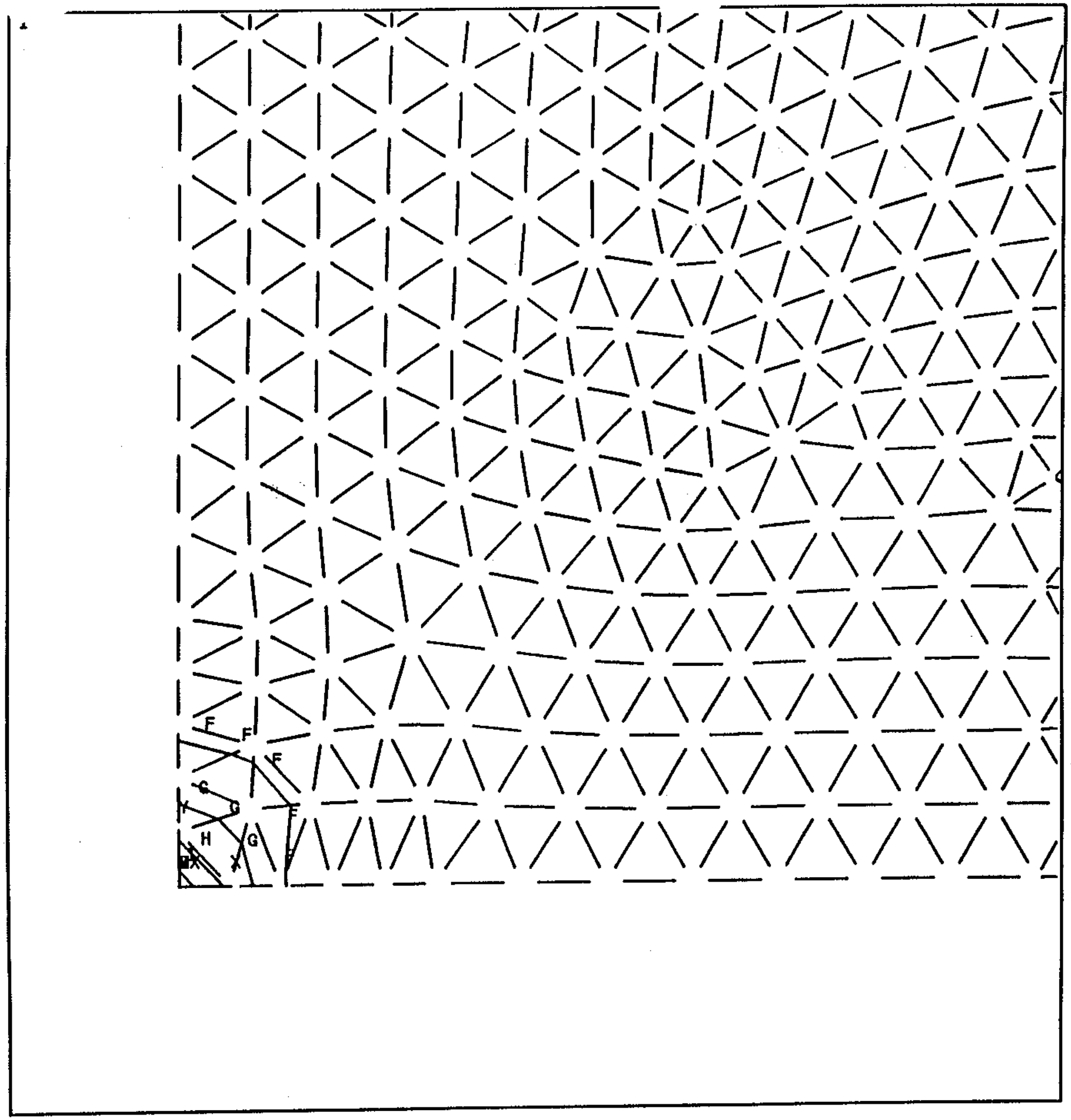


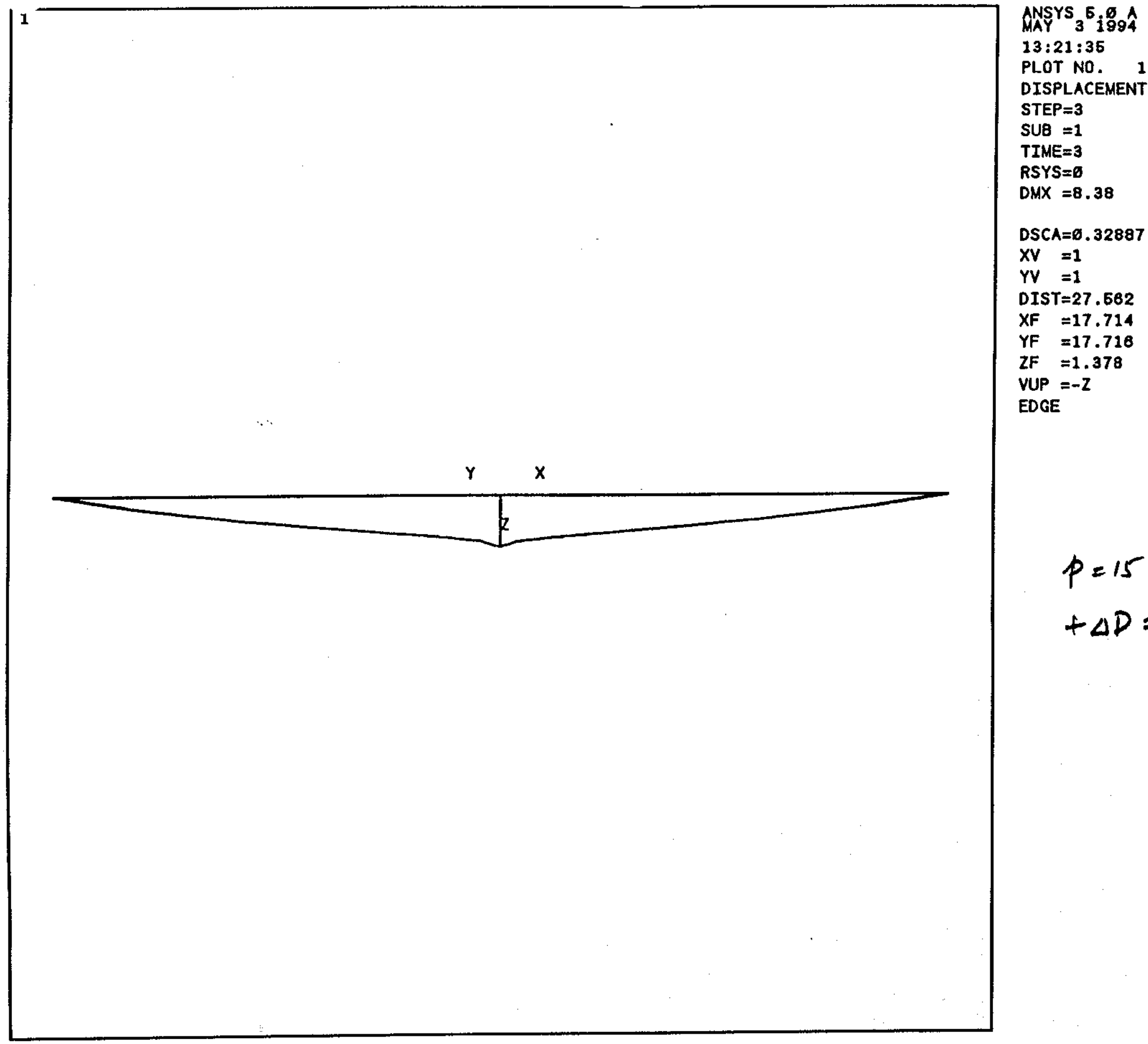
Figure 3. Deflection of the Window with 15 psi Load



ANSYS 5.0 A
MAY 3 1994
13:07:52
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SINT (AVG)
DMX =5.491
SMN =125136
SMX =208063
A =129742
B =138957
C =148171
D =157385
E =166599
F =175813
G =185027 $\approx \epsilon = 2\%$ 1.5%
H =194241
I =203455
(psi)

$p = 15$ psi.

Figure 4 stress plot for 15 psi Loading



$p = 15$ psi

$+\Delta D = 3''$

F 5 Deflection for 15 3" extra displacement

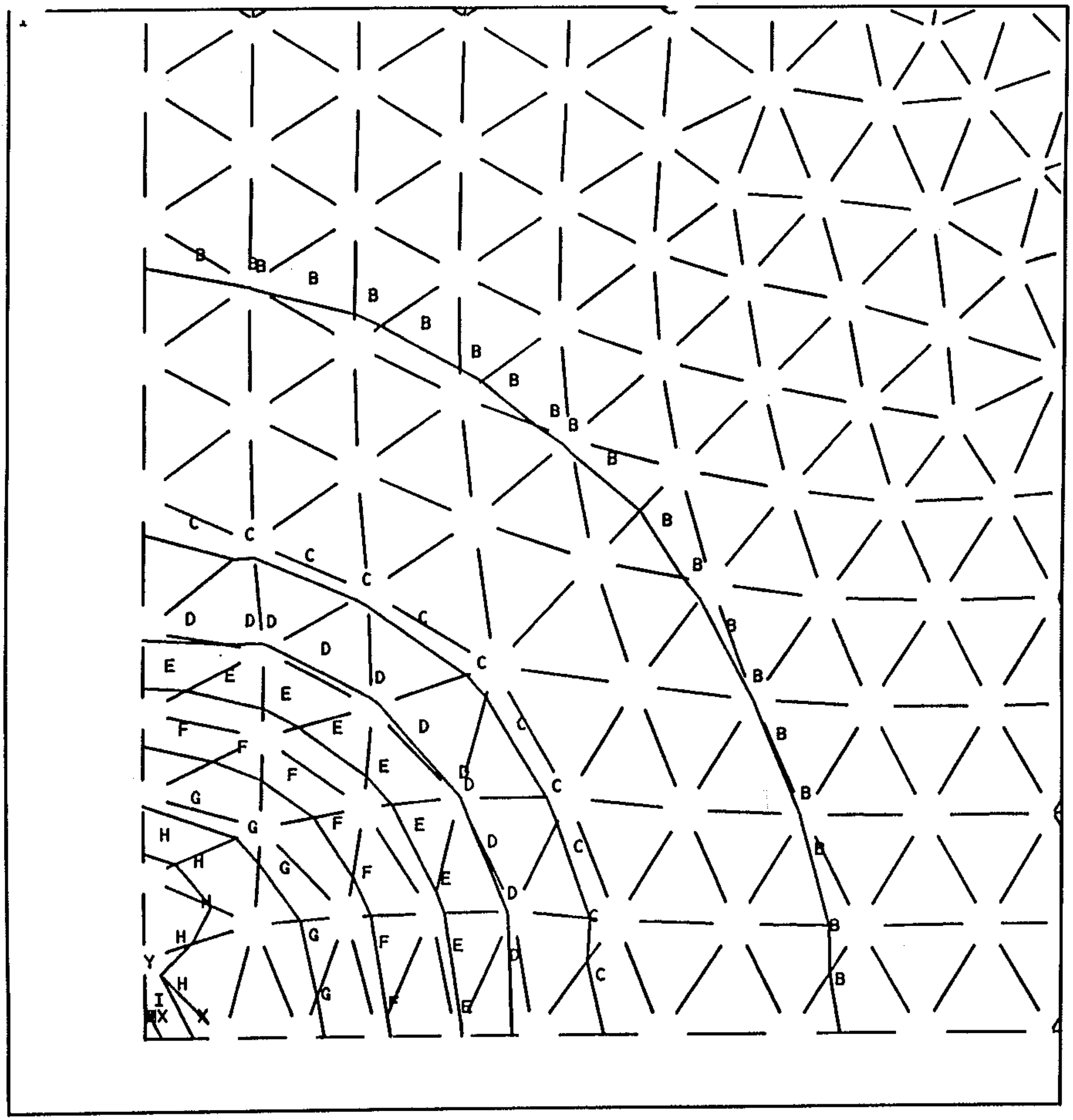


Figure 6 stress plot For 15 psi + 3" extra displacement

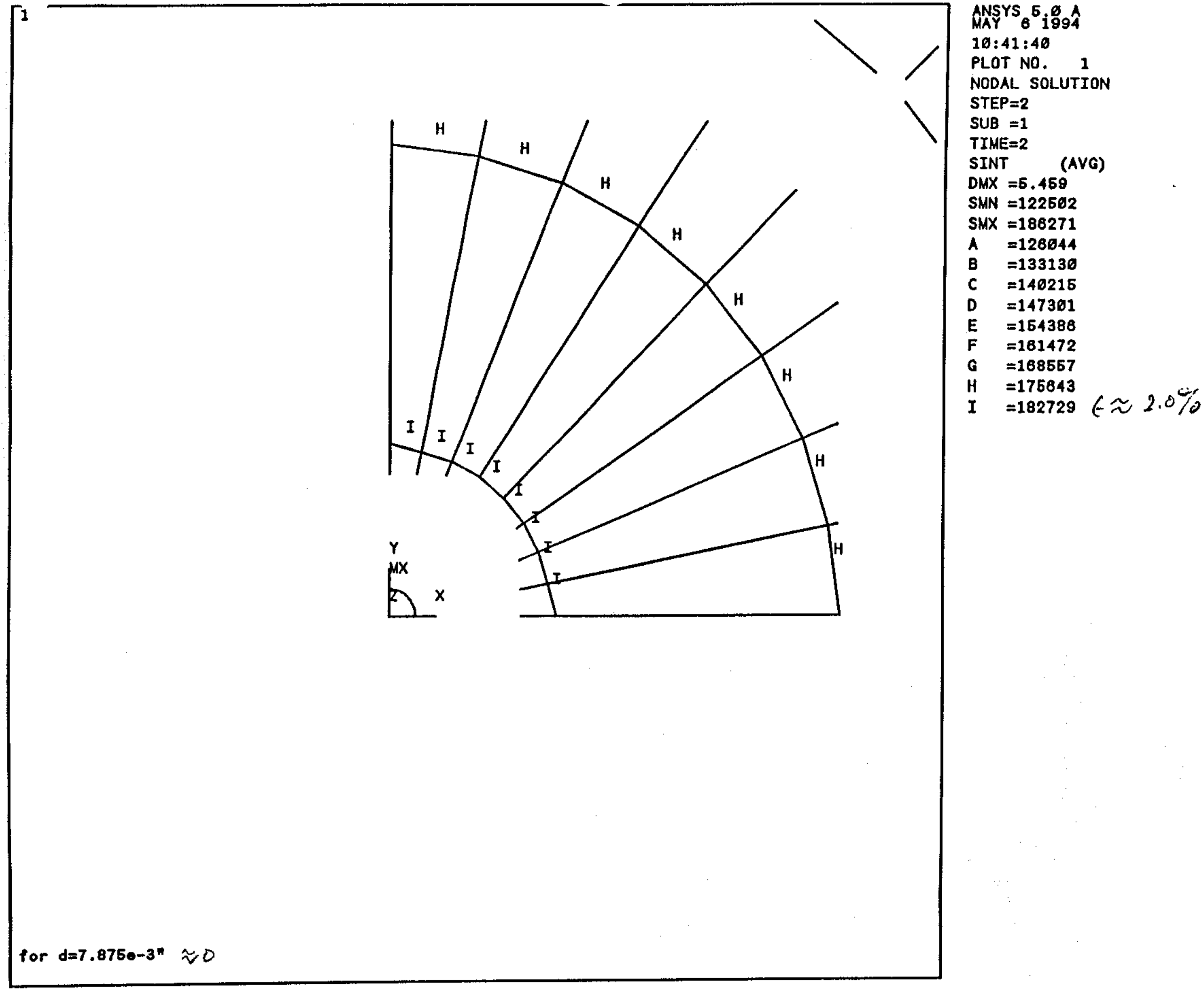


Figure 7. Stress plot for D CH 1=0 (15 psi)

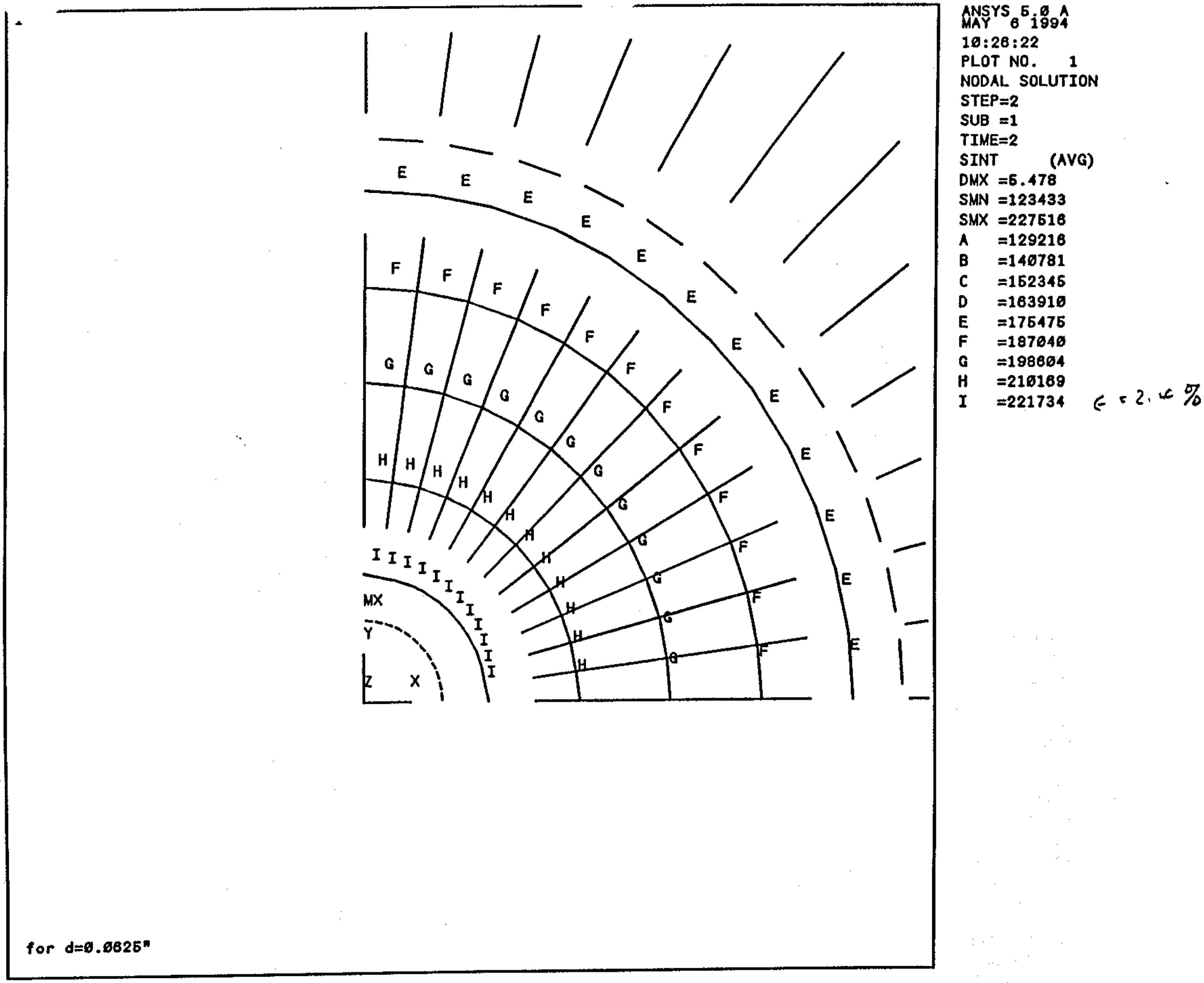


Figure 8 Stress plot For Hole D=0.0625" (15psi)

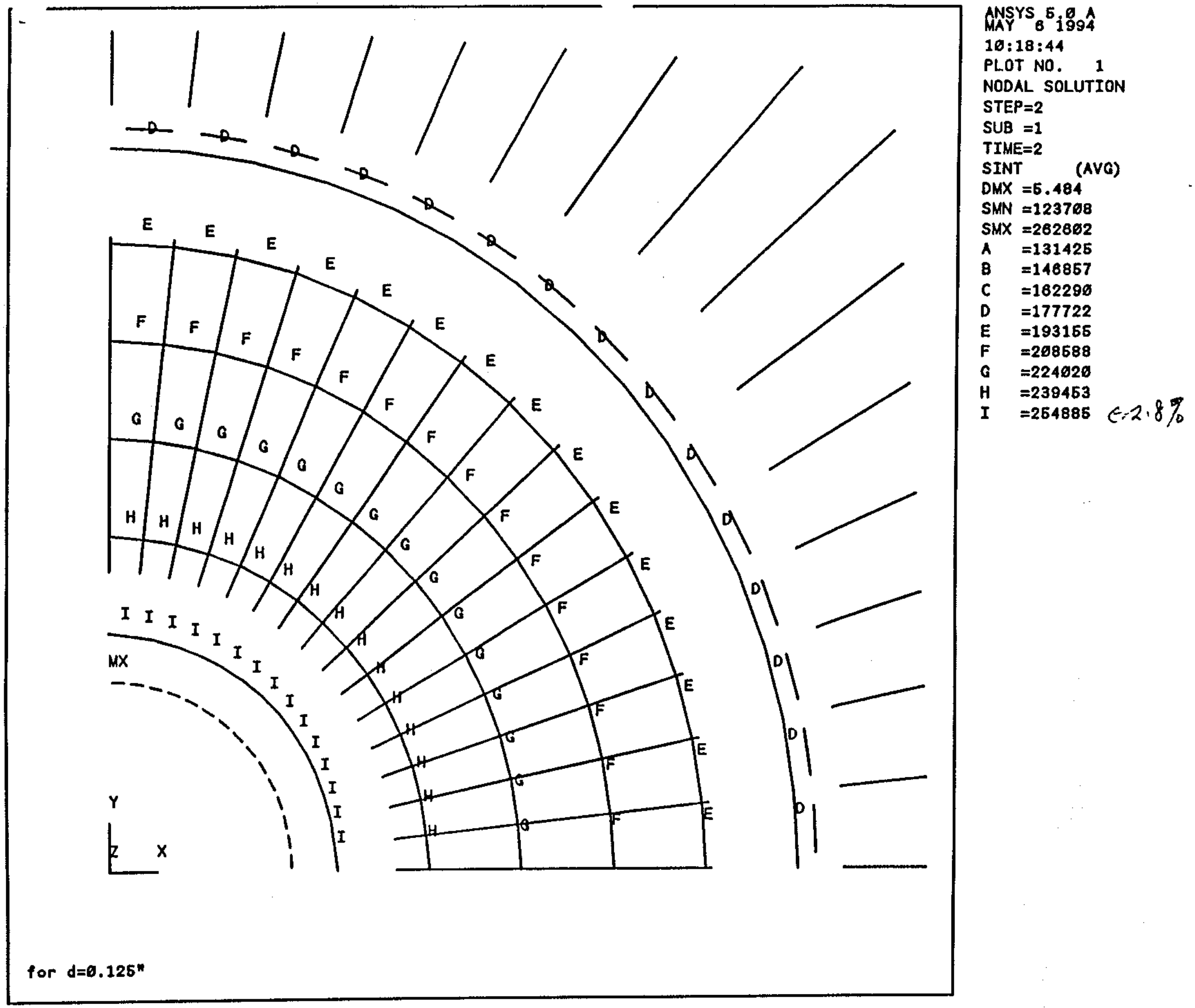


Figure 9 Stress plot for H ≥ D = 0.125" (15 psi)

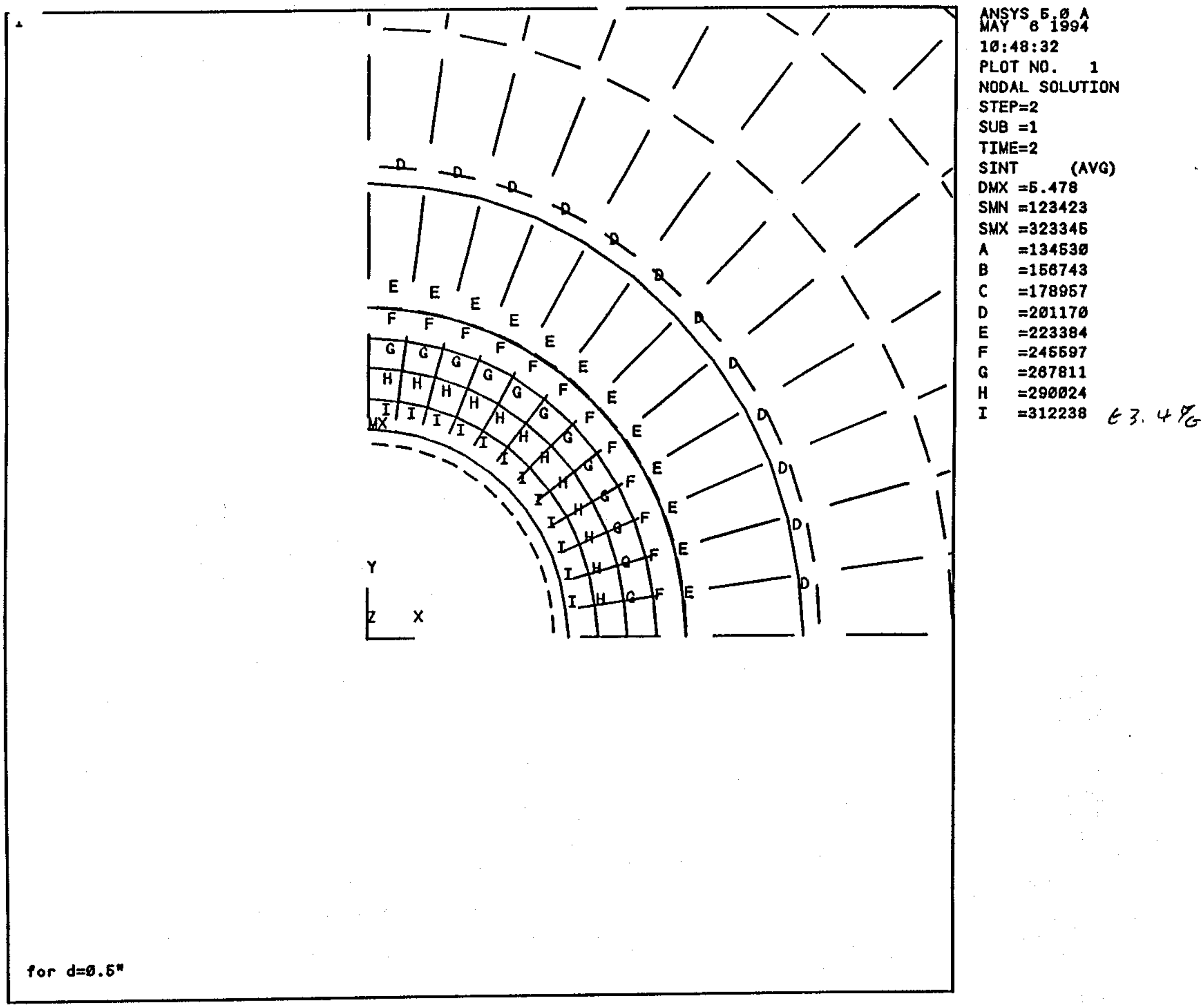
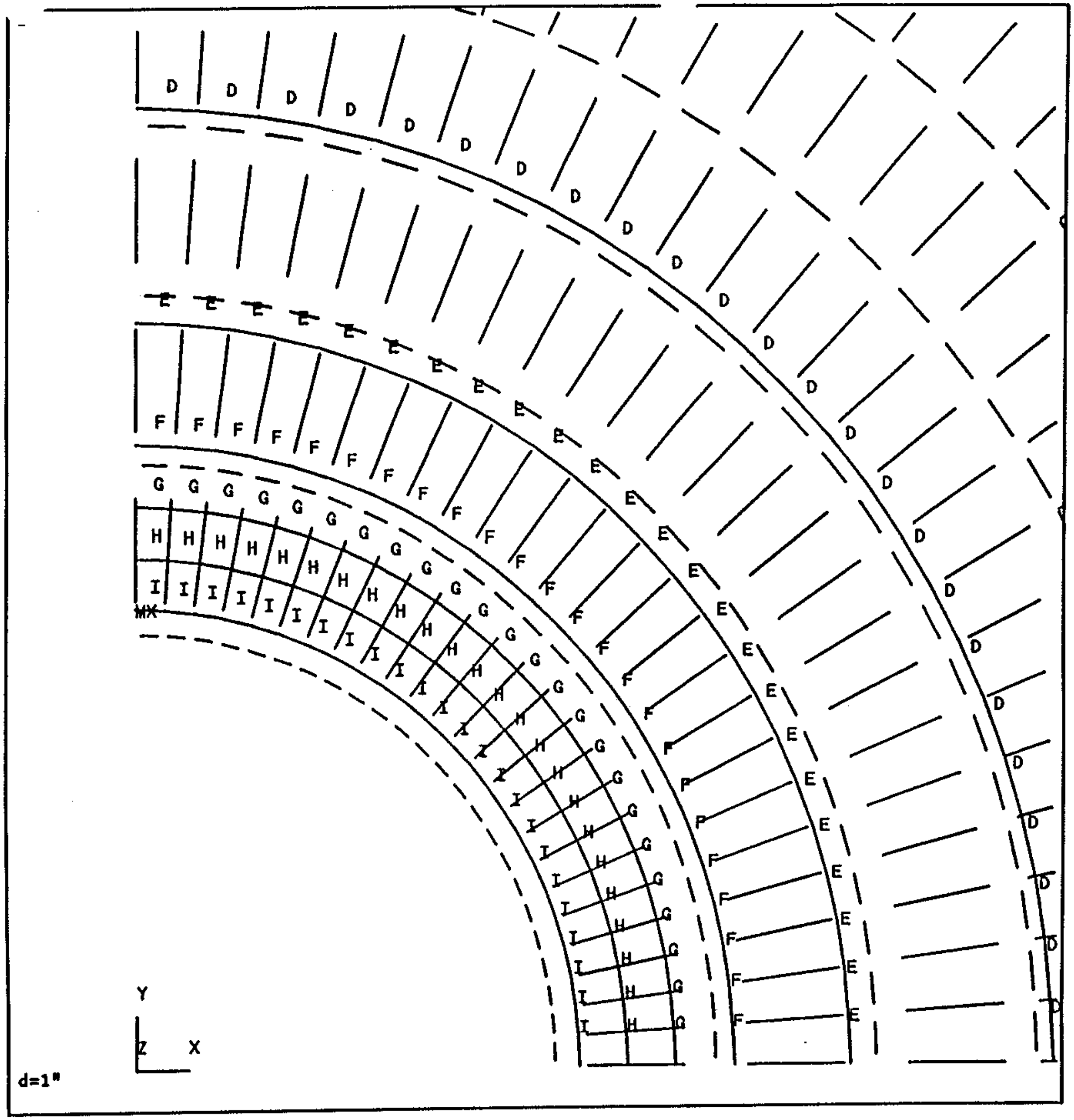
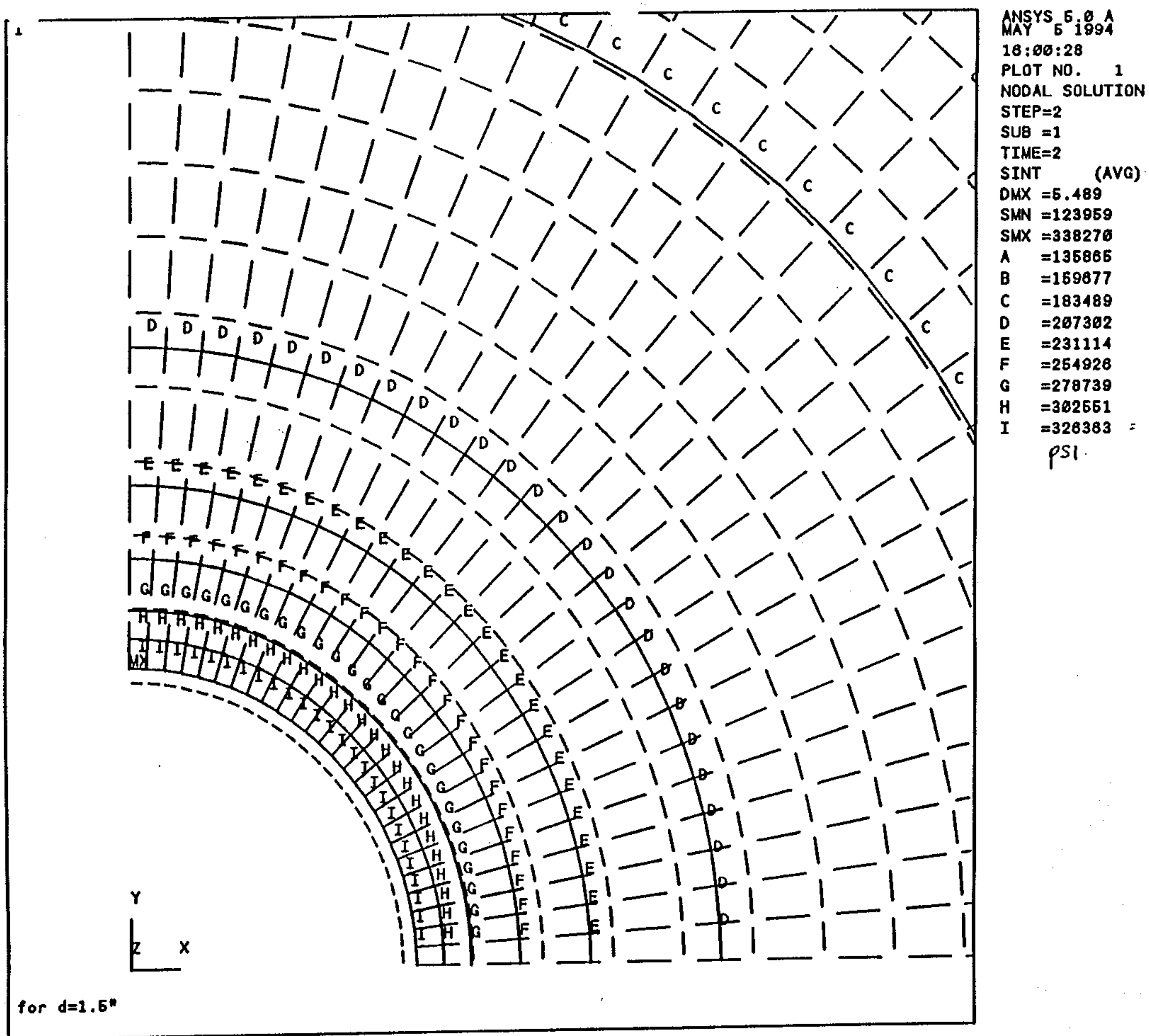


Figure 10 Stress Plot For Hole D=0.5" (15psi)



ANSYS 5.0 A
MAY 5 1994
15:21:44
PLOT NO. 1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
SINT (AVG)
DMX =5.49
SMN =123975
SMX =334805
A =135687
B =159113
C =182538
D =205964
E =229390
F =252815
G =276241
H =299666
I =323092 $\simeq 3.6\%$

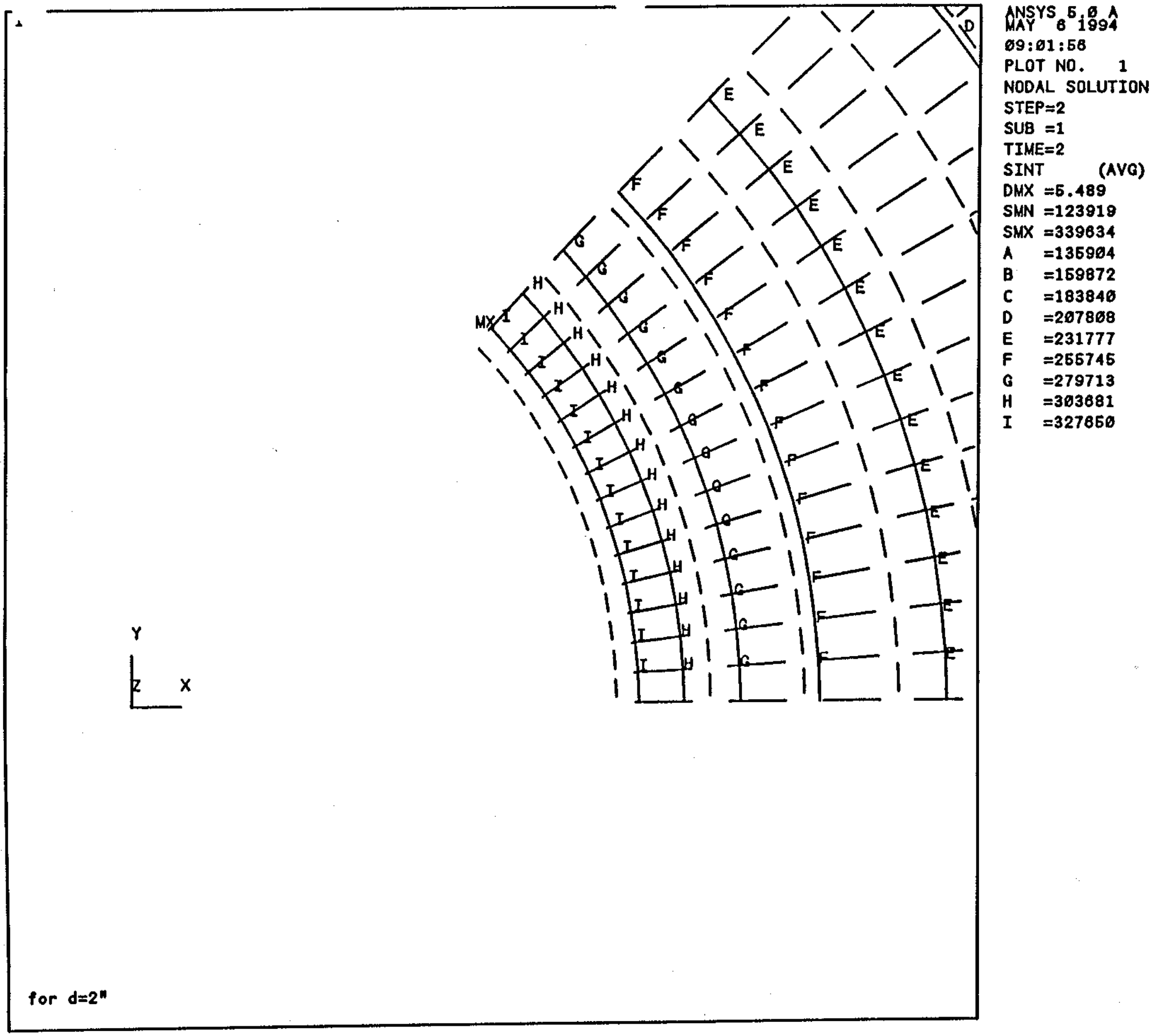
igure 11 stress ~~plot~~ for Hole size = 1" (15 psi)



= $\epsilon \approx 3.6\%$

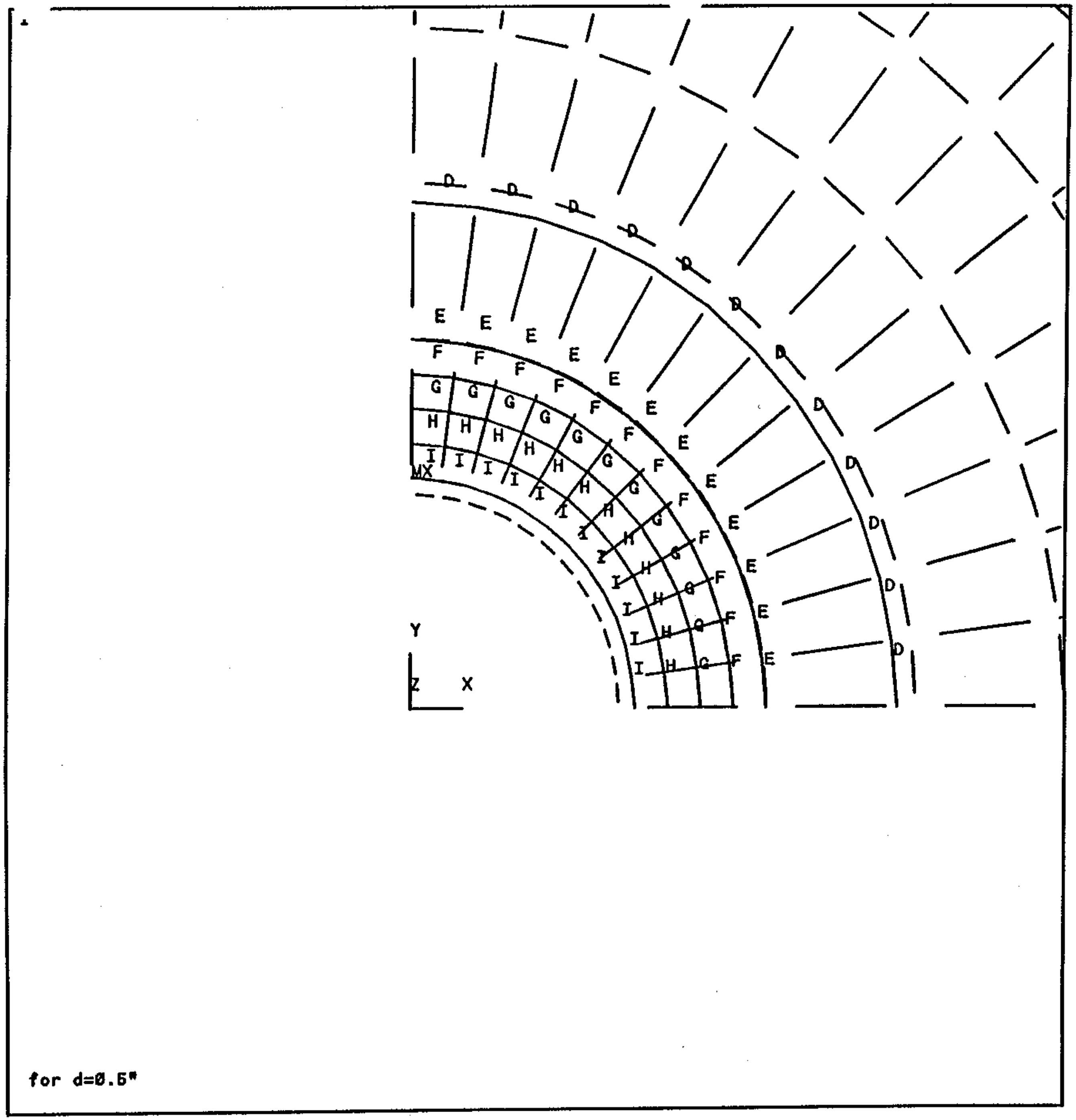
psi

Figure 13 Stress plot for hole size = 1.5" (15 psi)



$\epsilon = 3.7\%$

Figure 13. Stress plot ~~for~~ ~~Hole~~ size = 2" (15 psi)



ANSYS 5.0 A
MAY 6 1994
10:48:32
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SMN =123423
SMX =323345
A =134530
B =156743
C =178957
D =201170
E =223384
F =245597
G =267811
H =290024
I =312238 ε3.4%

Figure 10 Stress Plot For Hole D = 0.5" (15 psi)